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NAT'L INST OF STANDARDS & TECH R.I.C.
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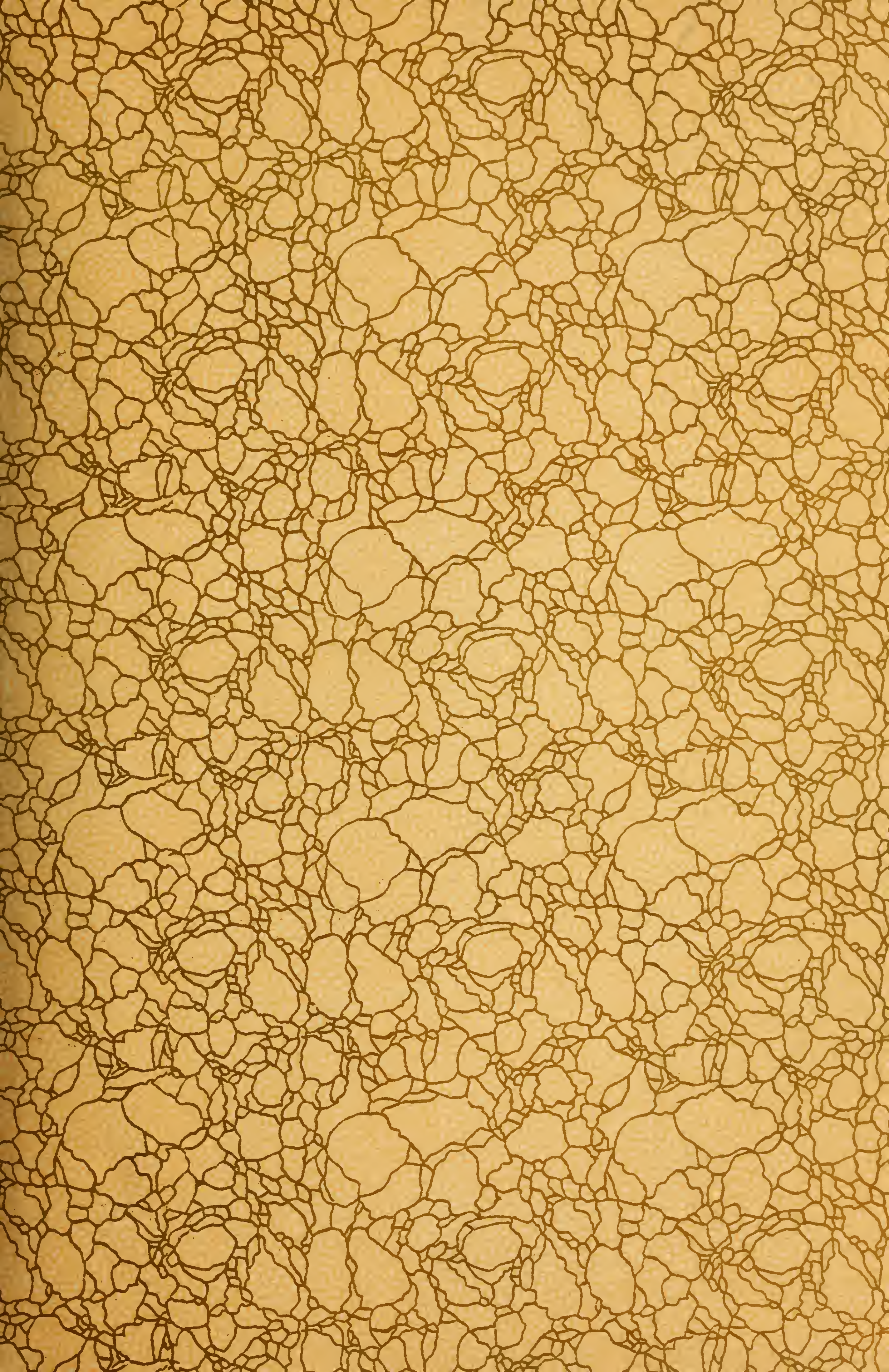
/Bulletin of the Bureau of Standards
QC1 .U5 V6;1909-10 C.1 NBS-PUB-C 1905

DEPARTMENT OF COMMERCE AND LABOR

BULLETIN OF THE BUREAU OF STANDARDS

VOLUME 6
1909-10



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DEPARTMENT OF COMMERCE AND LABOR

BULLETIN
OF THE
BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

VOLUME 6
1909-10

WASHINGTON
GOVERNMENT PRINTING OFFICE
1910

National Bureau of Standards
SEP 2 1952
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DAYLIGHT EFFICIENCY OF ARTIFICIAL ILLUMINANTS.

By Herbert E. Ives.

Among students of illumination it is generally agreed that the best light for human use is daylight. Therefore the nearer an artificial light approaches daylight in color and distribution, the higher it should rank. There has been developed, however, no simple means of measuring an artificial light source in such a manner that a numerical value can be given to its approach in quality to daylight. In other words, there has been no basis for estimating the "daylight efficiency."

In so far as color is concerned, progress has recently been made along two lines which should make possible and profitable an attempt to supply this deficiency. On the side of physical research extended series of spectrophotometric measurements of daylight have been made, notably by E. L. Nichols. On the technical side there have been developed new illuminants of high efficiency, and of color considerably nearer daylight than those previously known.

The present investigation was prompted by the question whether it might not be possible, with some of the more efficient illuminants, to imitate daylight by the use of properly colored globes or screens, without lowering the resultant efficiency below that of some of the older sources. Knowing the spectral relation of a source to daylight, it is a simple problem to determine the spectral absorption necessary to reduce the light to daylight color. Knowing the intensity equivalent of the different colors of the spectrum, it is possible to determine the loss in intensity due to the use of the colored absorbing screen.

The problem up to this point is an entirely practical one. After having worked out some numerical values in the way described below, it occurred to the writer that the white light obtained in this manner might be used as a convenient measure of the quality of an artificial light. The ratio $\frac{\text{intensity of available white light}}{\text{total intensity of source}}$ offers itself as a measure of the illuminant's efficiency with regard to color.

In the following paper are given the results of applying this idea to a number of the more prominent artificial illuminants. Two methods are developed; the first method, suggested above, by a discussion of absorbing screens, applicable to sources with a continuous spectrum, and giving the actual available nonselective white light; the second method, by means of the primary color sensations, applicable to both selective and nonselective sources, and giving the amount of white sensation, in general only partly or not at all available.

FIRST METHOD.

White Light Efficiency as Obtained by the Discussion of Absorbing Screens.—If we assume the intensity of the daylight spectrum to be unity at all points, the spectral intensity of any other light, as determined by the spectrophotometer, may be plotted on such a scale that the lowest point of the resultant curve is also unity. The colored screen which in combination with the source will transmit light of daylight color is the one whose percentage transmission at each point of the spectrum is the reciprocal of the ordinate of the illuminant's spectral curve. The first step in the artificial production of daylight by this method is therefore the determination of the spectral relationship of artificial sources to daylight. For this purpose is available the work of E. L. Nichols on average daylight in terms of the acetylene flame. Average daylight as determined by Nichols has the following intensities throughout the spectrum as compared with acetylene, equality being assumed, according to the usual practice, at .59μ.[1]

.725	.620	.590	.530	.460	.420	.390	μ
.450	.865	1.00	1.34	2.07	2.59	2.63	

Other light sources may be compared in the spectrophotometer with acetylene, and hence with daylight.

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[1] Transactions of the Illuminating Engineering Society, May, 1908.

Measurements of several illuminants, gas, glow lamps, etc., are given in the paper referred to. The electric glow lamps are not, however, specified according to watts per candle, the only exact mode of specification where relative color values are to be considered, and the Welsbach mantles are not classified according to cerium content, which determines the color. The writer, therefore, thought it worth while, for the purposes of this paper, to make spectrophotometer measurements, against acetylene, of carbon, tungsten, and other glow lamps at the exact watts per candle at which each is rated for commercial comparison, and of a Welsbach mantle whose cerium content is known.

The carbon and tungsten lamps were measured for watts per mean horizontal candle, and were 4 and 3.1 for the carbon, 1.25 for the tungsten. The mean spherical values were obtained by the use of reduction factors. The metallized and tungsten lamps were measured directly for mean spherical candlepower on an integrating photometer. The Welsbach mantle contained ¾ per cent cerium, being the mantle recommended for residential illumination by the Welsbach Company.

The measurements were made with a Lummer-Brodhun spectrophotometer; a tungsten lamp at constant voltage was used as a comparison source, and the substitution method was used. Special care was taken to exclude the effect of scattered light at the ends of the spectrum, by the use of colored glasses between the eye and eye slit. Measurements were carried to $.67\mu$ in the red and to $.42\mu$ in the blue.

The results of these measurements are given in Tables I and II; Table I in terms of acetylene, Table II in terms of average daylight, assuming the daylight acetylene ratios determined by Nichols.

It will be observed that if we plot as curves the data of Table II, the lowest point of all the curves is in the blue. In order, therefore, to determine the appropriate absorbing screens, these curves must be drawn with a point in the extreme blue made equal to unity. The choice of this point is largely arbitrary. The shorter the wave length chosen the smaller the percentage transmission of the absorbing screen for the other portions of the spectrum. A point should therefore be chosen of as long a wave length as possible without too great a loss of blue light. In the present paper the "equality point" has been taken as .42μ. This is one of the points measured in Nichols's daylight investigation, and is the point beyond which the average daylight curve takes more nearly the slope of the usual artificial sources. When screened from

TABLE I.

Spectrophotometer Measurements of Various Artificial Lights Against Acetylene.

	Source.	.42	.46	.50	.55	.59	.62	.65	.67μ
1	Glow lamp, carbon, 4.85 watts per mean spherical cp	.463	.580	.770	.875	1.00	1.11	1.19	1.26
2	Glow lamp, carbon, 3.75 watts per mean spherical cp	.463	.582	.755	.880	1.00	1.08	1.17	1.23
3	Glow lamp, metallized, 3.1 watts per mean spherical cp	.530	.635	.780	.905	1.00	1.085	1.15	1.17
4	Glow lamp, tantalum, 2.4 watts per mean spherical cp	.555	.680	.812	.920	1.00	1.055	1.12	1.13
5	Glow lamp, tungsten, 1.30 watts per mean spherical cp	.700	.815	.875	.945	1.00	1.05	1.08	1.11
6	Acetylene	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
7	Welsbach mantle, ½ per cent cerium	1.28	1.40	1.42	1.22	1.00	.89	.73	.64
		.4358μ		.5461μ		.5780μ			
8	Mercury arc (Nichols)	13.53		5.75		1.00			

TABLE II.

Light Sources Compared with Average Daylight.

	Source.	.42	.46	.50	.55	.59	.62	.65	.67μ
1	Glow lamp, carbon, 4.85 watts per mean spherical cp	.231	.280	.488	.735	1.00	1.27	1.45	1.52
2	Glow lamp, carbon, 3.75 watts per mean spherical cp	.234	.285	.490	.750	1.00	1.25	1.45	1.55
3	Glow lamp, metallized, 3.1 watts per mean spherical cp	.251	.285	.485	.750	1.00	1.25	1.38	1.55
4	Glow lamp, tantalum, 2.4 watts per mean spherical cp	.258	.318	.504	.758	1.00	1.22	1.34	1.50
5	Glow lamp, tungsten, 1.30 watts per mean spherical cp	.325	.375	.540	.780	1.00	1.21	1.47	1.70
6	Acetylene	.500	.455	.622	.825	1.00	1.18	1.35	1.50
7	Welsbach mantle, ½ per cent cerium	.645	.640	.884	1.00	1.00	1.00	.98	.98
		.4358μ			.5461μ		.5780μ		
8	Mercury arc (Nichols)	7.88			5.00		1.00		

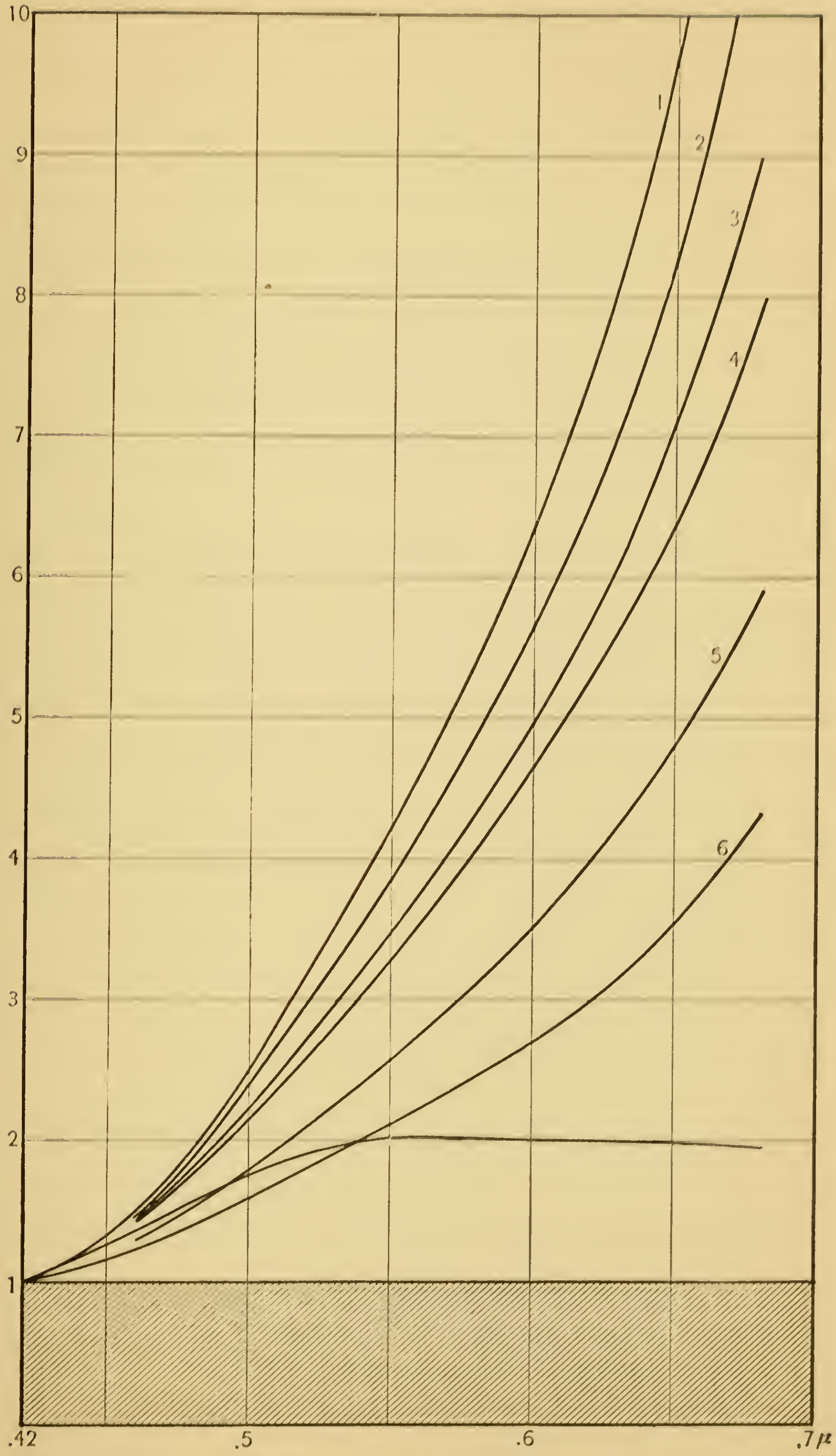

Fig. 1.—*Curves Showing Amount of Spectra of Various Light Sources which must be Absorbed to Leave White Light.*

this point, the deficiency in blue sensation of any of the ordinary sources is less than 2 per cent, a quantity small enough to be considered negligible. A different choice of equality point will of course lead to numerically different results, a matter to be treated again in the discussion of the second method.

In Fig. 1 the data of Table II are plotted on this basis. The area of each curve above the shaded area represents the portion of the illuminant's spectrum which must be removed by absorption to reduce it to identity with the daylight spectrum. The colored glass to effect this is one whose transmission is the reciprocal of the ordinate of the curve in question at each point.

Having obtained the properly colored glass to effect the absorption, we now wish to know the intensity value of the resultant artificial daylight. This we shall compare with the intensity of the unscreened source. We do this by considering the intensity value of the different spectral colors, and the resultant loss in total intensity when the various portions of the spectrum are reduced in the proportion indicated above. The method is indicated in Fig. 2. The shaded area represents the spectrum of white light expressed in terms of luminosity; it is, in other words, the sensibility curve of the normal eye referred to white light[2]. The areas inclosed by the outlined curves and the axis of abscissæ are the resultant of increasing the ordinates of the sensibility curve in the proportion indicated by the curves of Fig. 1. The areas of the outlined curves are therefore proportional to the intensity of the unscreened sources, the shaded area to the intensity of the white light remaining after screening. The ratio of the shaded to the unshaded area gives the value

$$\frac{\text{Intensity of White Light obtained by Screening from } .42\mu}{\text{Intensity of unscreened source.}}$$

This quantity, for which the values for several sources are given in Table III, column 6, is an indication of the loss in efficiency which may be expected upon producing artificial daylight by the use of colored absorbing screens. The figures also lend themselves to giving a value to a light source considered from the standpoint

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[2] Abney, Phil. Trans. Roy. Soc. **193**, p. 286; 1900. This curve is for high intensities where the Purkinje effect is not noticeable.

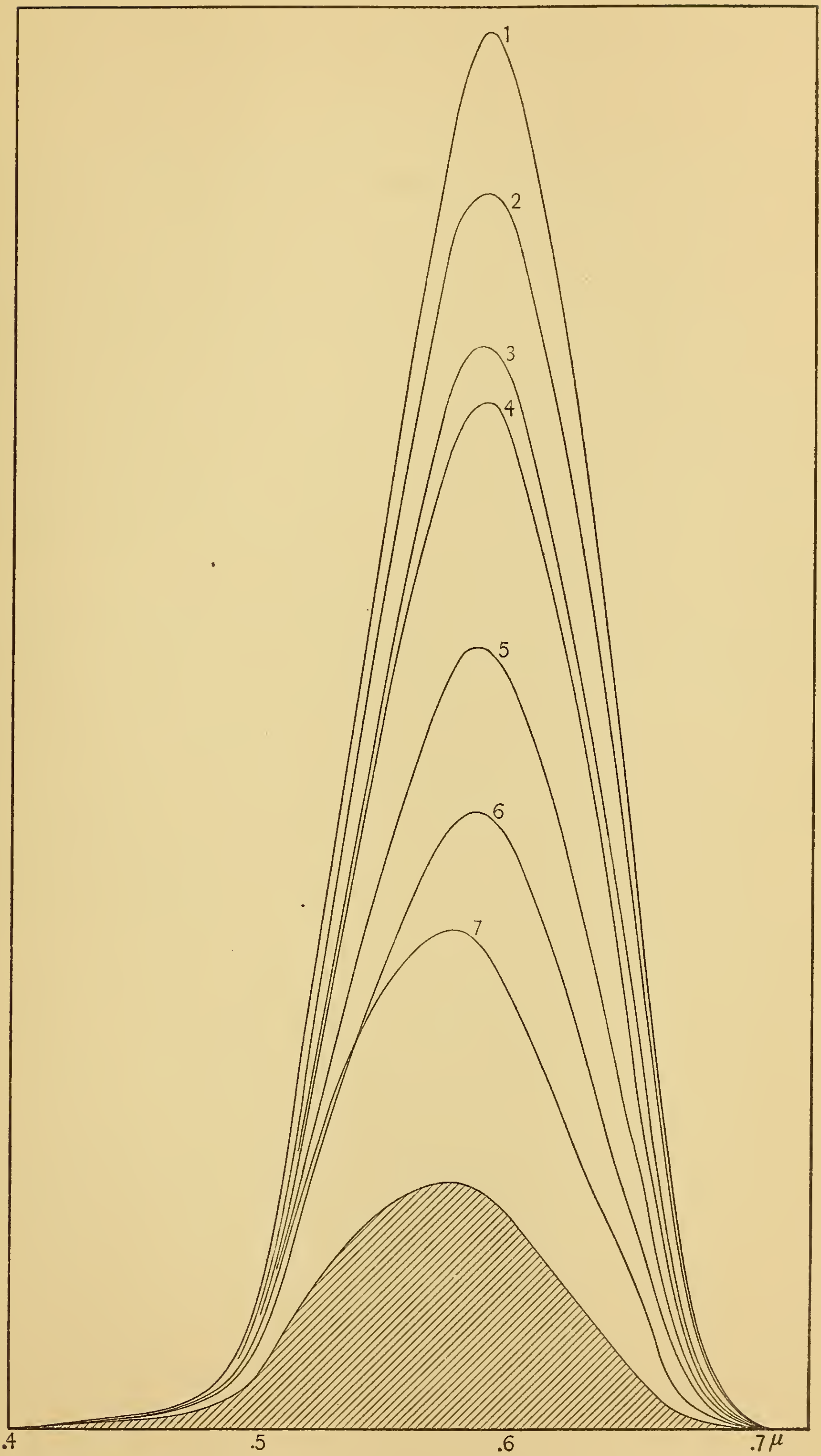

Fig. 2.—*Excess of Colored Light in Various Light Sources, Represented in Terms of Luminosity.*

of its approach in color to daylight. They may in fact be called the "daylight" or "white light efficiencies," as is here done.

TABLE III.

Color Sensation Values, White Sensation and White Light Efficiencies.

	Source.	1 Sensations.			2 Luminosity.	3 Hue.	4 White sensation.	5 White sensation efficiency.	6 White light efficiency.
		Red.	Green.	Blue.					
1	Glow lamp, carbon, 4.85 watts per mean spherical cp	46.5	39.7	13.8	44.1	.588μ	13.7	31.0	19.3
2	Glow lamp, carbon, 3.75 watts per mean spherical cp	45.9	39.4	14.7	43.5	.588	14.5	33.4	21.2
3	Glow lamp, metallized, 3.1 watts per mean spherical cp	44.8	39.7	15.5	42.9	.585	15.3	35.8	24.6
4	Glow lamp, tantalum, 2.6 watts per mean spherical cp	44.2	39.8	16.0	42.6	.585	15.9	37.3	26.3
5	Glow lamp, tungsten, 1.56 watts per mean spherical cp	42.8	39.1	18.1	41.5	.584	18.0	43.5	33.2
6	Acetylene	40.8	38.3	20.9	40.1	.583	20.7	51.7	42.0
7	Welsbach mantle, ¾ per cent cerium	37.4	37.8	24.8	37.4	.577	24.5	65.5	50.5
8	Mercury arc (Nichols)	22.4	23.6	54.0	23.0	.480	18.0	78.8	0
9	Average daylight	33.3	33.3	33.3	33.3	......	33.3	100	100

TABLE IV.

Source.	1 Watts per mean spherical candle.	2 White sensation w. p. s. c.	3 White light w. p. s. c.
Carbon glow lamp	4.85	15.6	25.1
Carbon glow lamp	3.75	11.25	17.7
Metallized glow lamp	3.1	8.65	12.6
Tantalum	2.5	6.7	9.5
Tungsten glow lamp	1.56	3.6	4.7

In Table IV, column 3, the results are applied to the electric glow lamps in combination with their energy consumption, giving what may be called "White light watts per candle." It will be observed that the question which prompted the investigation is answered. The "White light watts per candle" of the tungsten lamp is less than the watts per candle of the "4-watt" carbon lamp, indicating that artificial daylight should be no more expensive than was electric light not long ago. This of course assumes the possibility of obtaining colored glass of exactly the absorption required.

This method of obtaining efficiency in terms of daylight, namely, by the use of colored absorbing screens, is of more practical than scientific interest. As has been pointed out, the numerical values will vary with the wave length chosen as the equality point. A method giving a relationship to daylight independent of choice of coordinates would in some ways be preferable. Moreover, the above method gives the value zero to selective sources, where by selective source is meant one of the type of the mercury arc whose spectrum consists of bright lines with no continuous background. Selective sources, however, actually excite all three primary color sensations, giving some sensation of white. The attempt to find a method applicable to such sources has led to a second method of finding color efficiency, namely, the method of color sensations, which will now be described.

SECOND METHOD.

White Light Efficiency Obtained by Means of the Primary Color Sensations.—Any color can be matched by a mixture of white light and one ray of the spectrum.[3] The intensity of this white compared with the intensity of the colored source gives a white light efficiency which is obtainable with all types of selective and non-selective sources. We may imagine this accomplished experimentally in the following manner: Given a standard white light, let the intensity of the source in question be measured against the standard, say with a flicker photometer or by some other method independent of color difference. By means of a spectroscopic device, superpose on the white light colored light from a narrow region of the spectrum. Alter the intensity of the white and the wave-length and intensity of the spectral light until a visual match is obtained for both color and intensity. The ratio of the intensity of the white used in this match to the intensity of the source is a white light efficiency independent both of the character of the source and of any arbitrarily chosen "equality point."

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[3] Abney, "Color Measurement and Mixture," Chapter XIII. The only exceptions are furnished by colors of purple hue, in which the green sensation is smaller than either the red or the blue. These must be measured in terms of their complementaries. Purple light sources are not met with in ordinary experience, and need not be considered.

The experimental difficulties in the way of carrying out the procedure as outlined are great, chiefly because of the difficulty of producing a white light standard. The whole process may, however, be carried out indirectly by means of the color sensation curves of the normal eye, as determined by König. These curves, as modified by Exner, are reproduced in Fig. 3.[4] They show the amounts of each of the primary sensations—red, green, and blue—which are excited by the various portions of the spectrum. They are drawn, according to the usual convention, with the three areas equal for white light. White then being equal excitation of the three sensations, all other colors can be expressed in terms of the relative proportions of red, green, and blue sensation. Knowing the sensation values of a color, it is then possible to find from the curves a wave-length which, with white added, has the same proportionate parts of red, green, and blue as the color. In this manner the dominant hue of the color is determined, and the amount of white light to be added to the dominant hue. It is then necessary to have the intensity values of the three sensations. Applying these to the color, and then to the white added

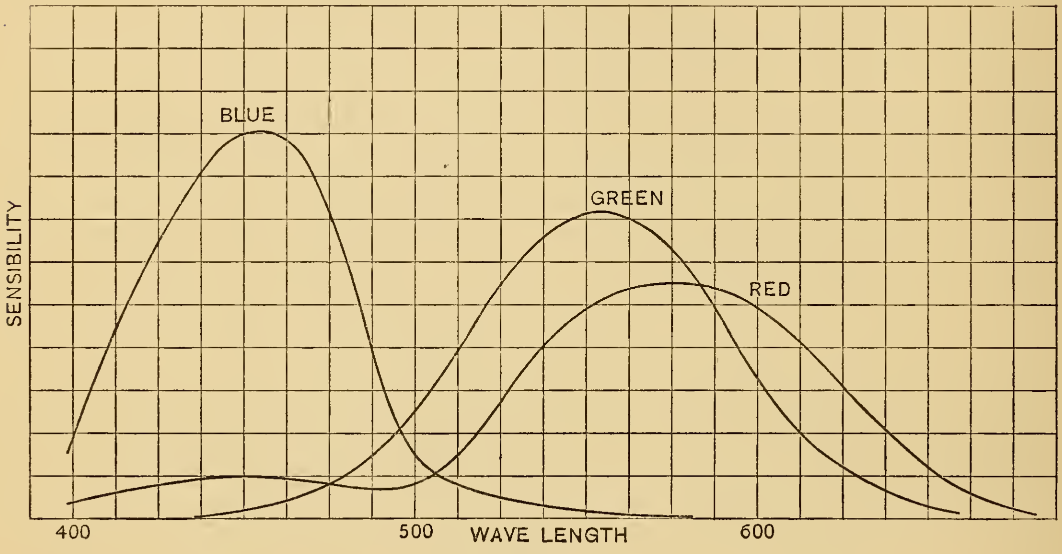

Fig. 3.

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[4] F. Exner, Sitzungsberichte der Akademie der Wissenschaften, Wien, 3, p. 857; 1902.

to the dominant hue, the desired ratio of intensities may be obtained.

In order to apply the method it is necessary to know the sensation values of a color and the luminosity values of the three sensations. To obtain the sensation values of a color two procedures are open. If spectrophotometric measurements are available, the sensation values may be obtained by multiplying the sensation curve ordinates at each wave-length by the spectral intensity of the color as compared with the standard. A second method is to measure the color by means of a color-mixing instrument, the sensation value of whose colors are known. In the latter method we again meet the difficulty that no standard white light is available. In the present investigation the sensation values were obtained by applying the spectrophotometric values obtained above to the sensation curves. As to the luminosity values of the sensations Abney has determined that for sunlight the values are[5]—

Red.	Green.	Blue.	
65.73	33.83	.44	(= 100.00)

These values are used in the present paper on the assumption that they will be substantially the same for average daylight.

To illustrate the method of procedure, the work for acetylene is given in full. Applying the values of Table II to the sensation curves, the sensation values (that is, the areas of the new curves, as measured with a planimeter) found for acetylene were—

Red.	Green.	Blue.
94	88	48

Giving to each sensation its appropriate luminosity value, the luminosity of the acetylene color (in arbitrary units) was 92.1. By trial it was found that if 47.6 parts of white were subtracted from the color the remaining sensation values—i. e., 46.4, 40.4, .4—were in the proportion of the sensations at .583μ. The luminosity or intensity ratio is therefore $\frac{47.6}{92.1}=51.7$, and the dominant hue is .583μ.[6]

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[5] Philosophical Transactions, loc. cit.

[6] The process of finding the dominant hue is much simplified by the use of Maxwell's color triangle.

This white light efficiency is obtainable for any type of source—for instance, the mercury arc, the values for which, calculated from spectrophotometer figures given by Nichols,[7] will be found in Table III along with values for the sources already evaluated according to Method I.

Comparison of the white-light efficiencies obtained in this way with those from the first method shows that in every case the second efficiency is higher than the first. It is clear why this should be so, for if we call the intensity of the white light obtained by the first method Iw_1, we have that the total color Ic (expressing it in intensity units) is equal to Iw_1 and the absorbed wave-lengths represented by the curves of Fig. 1 above the shaded area. This absorbed color is itself, not being a single spectrum ray, reducable to white light, say Iw_2 and a single wave-length. We may express this fact in the following equation:

$$\begin{aligned} Ic &= Iw_1 + Iw_2 + I_\lambda \\ &= I\mathrm{w} + I_\lambda. \end{aligned}$$

$I\mathrm{w}$ represents the total white sensation; Iw_1 represents the available nonselective white light; its value may be zero, as in the mercury arc.

The two kinds of white light efficiency or color efficiency may be conveniently designated as "White Sensation Efficiency" and "White Light Efficiency," the first being always larger than the second.

Before discussing the interpretation and utility of these quantities, it is of interest to note several points in connection with the characteristics of white light and white sensation as here distinguished. If we write the above equation $Ic - I_\lambda = I\mathrm{w}$ we express the condition for securing the largest possible amount of white sensation, namely, by subtracting light of one wave length. The nearest approach to this practicable is to subtract a wide band in the neighborhood of λ. Inspection of the sensation curves shows that with a yellowish source, such as a glow lamp, absorption of a band near .59μ would, while reducing the red and green sensations, have slight effect on the blue, while the uniform absorption of Method I wastes considerable of that already deficient sensation. It would therefore be possible, by selective screening, to secure nearly the whole of the white sensation value existing in the source. Since the white sensation value is the only white light value possessed by selective sources, and since the white sensation value may be nearly obtained by selective screening of continuous spectrum light sources, we might use the term "selective white" to designate it, although "white sensation" is preferred by the writer. It is of interest to note that with the sources considered—acetylene, etc.—if the equality point for screening is taken as about .455μ the resultant (slightly yellowish) white is of very nearly the white sensation value. For some practical purposes, therefore, the white sensation values might be assumed to be the available white, in the case of continuous sources.

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[7] Loc. cit.

It is possible to apply the first method to the color sensation curves, for the ordinates of the curves giving the sensation value for a source may be reduced from the same equality point in the proportions demanded by the curves of Fig. 1, their areas measured before and after reduction, and the luminosity values of the sensations applied as above. This was done as a check on the sensibility curve values, and the results agreed within the errors of measurement.

In Table III are given the sensation values of the various sources, their dominant hues, white sensation and white light efficiencies. The sensation values are so reduced that their sum equals 100 in each case. Column 4 (percentage white sensation) then expresses a purely hue or color efficiency, namely, $\frac{\text{white sensation}}{\text{total sensation}}$, where the sensations are assumed of equal value in white light. This ratio, not having a close connection with the problem of screening or with the possible experimental procedure outlined under Method II, has not been considered at length.

In Table IV are given the values of "white light" and "white sensation" watts per candle for the electric glow lamps.

DISCUSSION OF RESULTS.

Two methods have been developed for obtaining a measure of the approach of a light in color to daylight. Two values have been obtained for the quantity expressing the color efficiency. Their characteristics and interpretation are as follows:

1st. **The White Light Efficiency.**—Obtained by consideration of the white light available by the use of absorbing screens. The white light obtained is nonselective white light, spectrally identical with Nichols's "average daylight." The term "White Light Efficiency" is applied to the ratio

$$\frac{\text{Intensity of Nonselective White Light Available,}}{\text{Intensity of Source.}}$$

Its numerical value is dependent on the point of the spectrum at which absorption starts, and is zero for a bright line source. It is of practical importance as an indication of the loss in efficiency to be expected by producing "daylight" by the use of colored globes on artificial sources. As the white light obtained is identical with daylight, the "White Light Efficiency" is a good indication of a source's excellence for use where color discrimination is necessary. The larger the proportion of available white light the nearer will colors appear in their daylight values.

2d. **The White Sensation Efficiency.**—Obtained by consideration of the amount of white which with a spectrum color would match the light. The term is applied to the ratio

$$\frac{\text{Intensity of White Sensation.}}{\text{Intensity of Source.}}$$

The method is independent of any arbitrary screening point, and is applicable to all types of sources. The white sensation obtained indicates the color of the light or of a white surface illuminated by it. It gives no indication of the suitability of a source for color discrimination. The white sensation is larger than the white light given by Method I, and is as a rule only partly or not at all available as nonselective white light.

The question arises: Which of these efficiencies is it preferable to use? From a purely scientific standpoint the white sensation efficiency is preferable, because of its universal application and independence of arbitrary screening point. The white light efficiency, however, furnishes information of importance in the consideration of artificial illuminants, namely, on the merits of a source for the purpose of illuminating colored objects. A method to include both values would be superior to either alone, and an attempt to do this graphically is given in Fig. 4, in which some of the results of Table III are embodied. The rectangles indicate the white sensation efficiencies of the several sources, the shaded portions of the rectangles the white light efficiencies. The vertical lines and scales give the dominant hues. Inspection of the figures will show that they demonstrate in a rather striking way the relative qualities of the sources from the standpoint of their color. A light of the type of II, for instance, is one of bluish hue, of about 80 per cent white sensation, but a source not suited for color discrimination; a light of the type of III is one of yellowish hue, with a large amount of available white, and therefore suited to color discrimination. In daylight the white sensation and white light areas are identical.

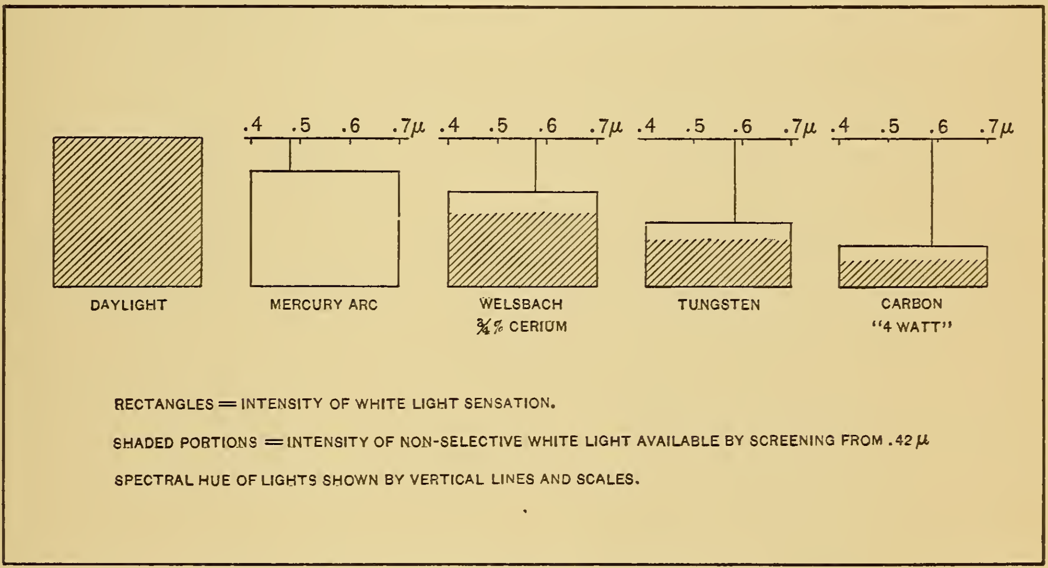

Fig. 4.

It is not claimed that this use of the white light efficiency in combination with the white sensation efficiency will lead to rigidly correct or strictly comparable results in all cases conceivable. For instance, a source consisting of a large number of bright lines evenly distributed through the spectrum would have zero white light efficiency, although it would be a pretty good light for color discrimination. This difficulty could, of course, be avoided by agreement on the number and closeness of lines which may be considered equivalent to a continuous spectrum for purposes of illumination. On the other hand, a source containing a large amount of available white may have such a spectral distribution as to be of less pleasant effect to the eye than one of smaller white light efficiency. This is, of course, rather a question of æsthetics or physiology than of physics. If we confine ourselves to the illuminants at present in use, this combination of the two efficiencies presents the color characteristics of interest to the illuminating engineer more accurately than any classification known to the writer, and is, therefore, thought worth presenting.

The values obtained in this paper are dependent on the correctness of several sets of data: On the measurements of daylight by E. L. Nichols; on the measurements of artificial sources by the writer; on the sensibility curve of the eye as given by Abney; on the color sensation curves of König and Exner; on the luminosity values of the sensations as given by Abney. Future measurements or redeterminations may change the numerical values. The principles involved, however, remain the same, and the methods developed give, it is believed, a new and useful basis for the color comparison of artificial illuminants.

WASHINGTON, May, 1909.